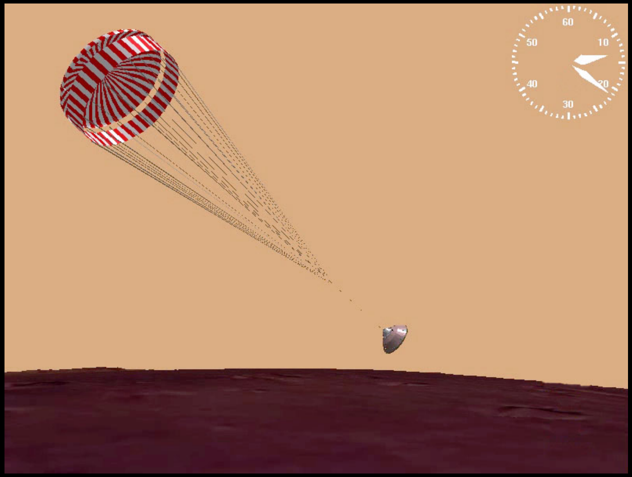
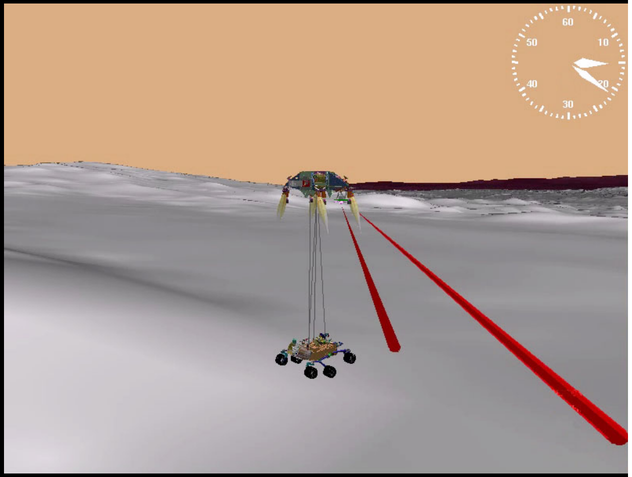
Flight Mechanics for Mission Scientists





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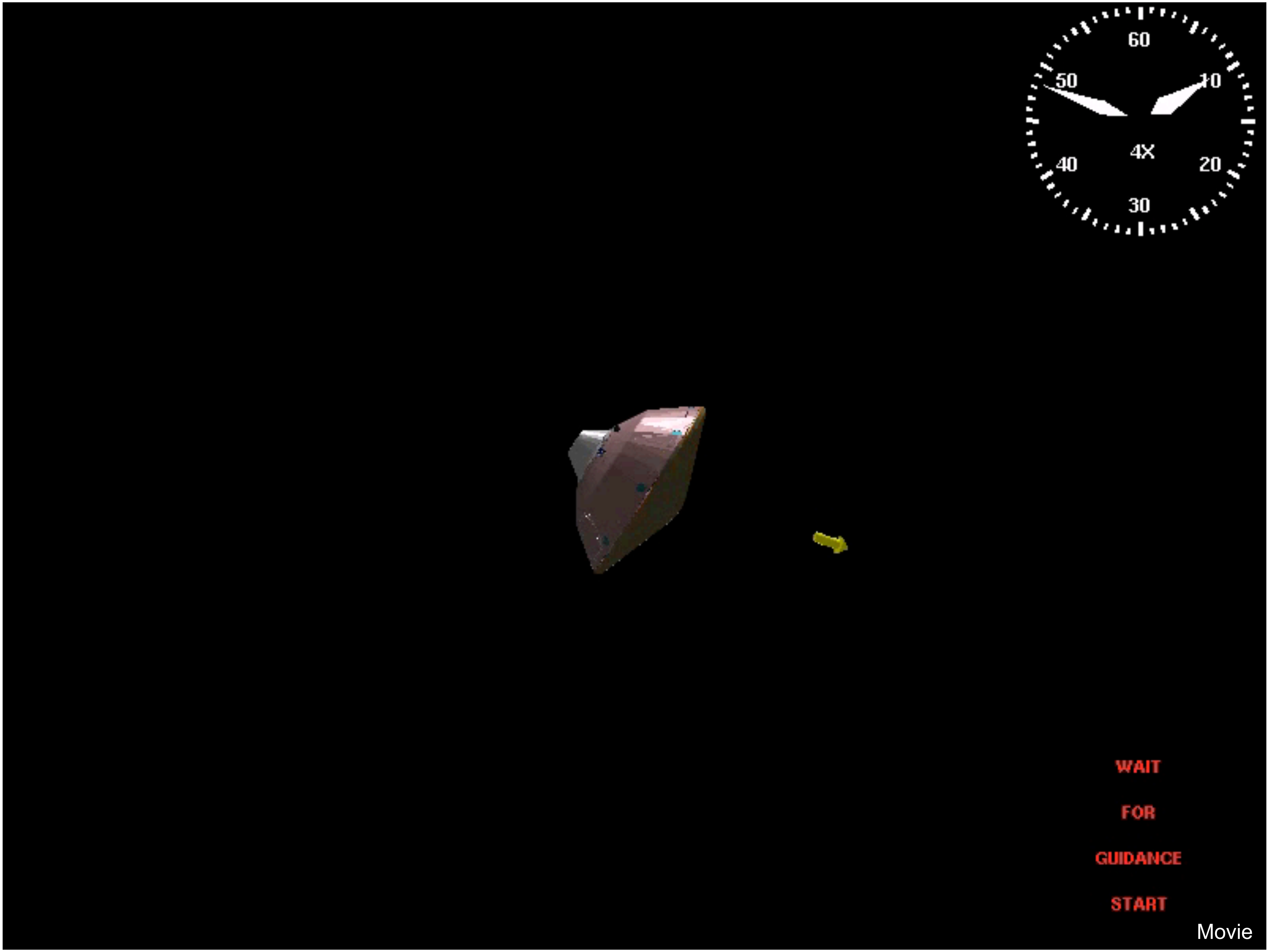
Version 2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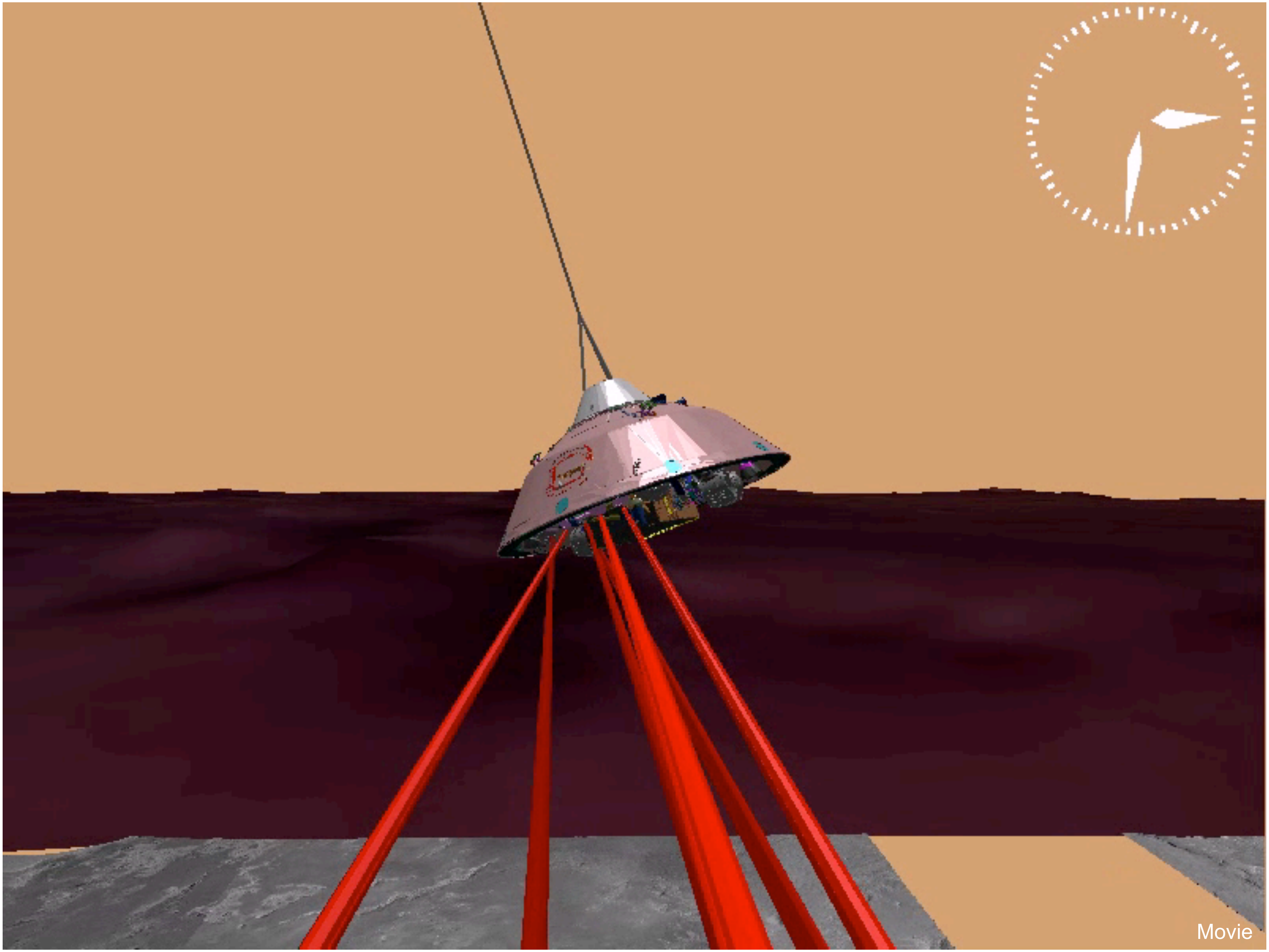
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Flight Mechanics

Definition
The branch of engineering that studies the motion of aerospace vehicles in flight when acted upon by gravitational, aerodynamic, propulsive, and other external forces.

In this lecture I will focus on the flight mechanics of entry and descent vehicles, with an emphasis on:

- State variables, equations of motion
- Aerodynamics
- *Improving communication between flight mechanics engineers and mission scientists*

State Variables

Twelve state variables completely define the motion of the vehicle:

u, v, w - vehicle's center of mass velocity vector

p, q, r - vehicle's rotation rate vector

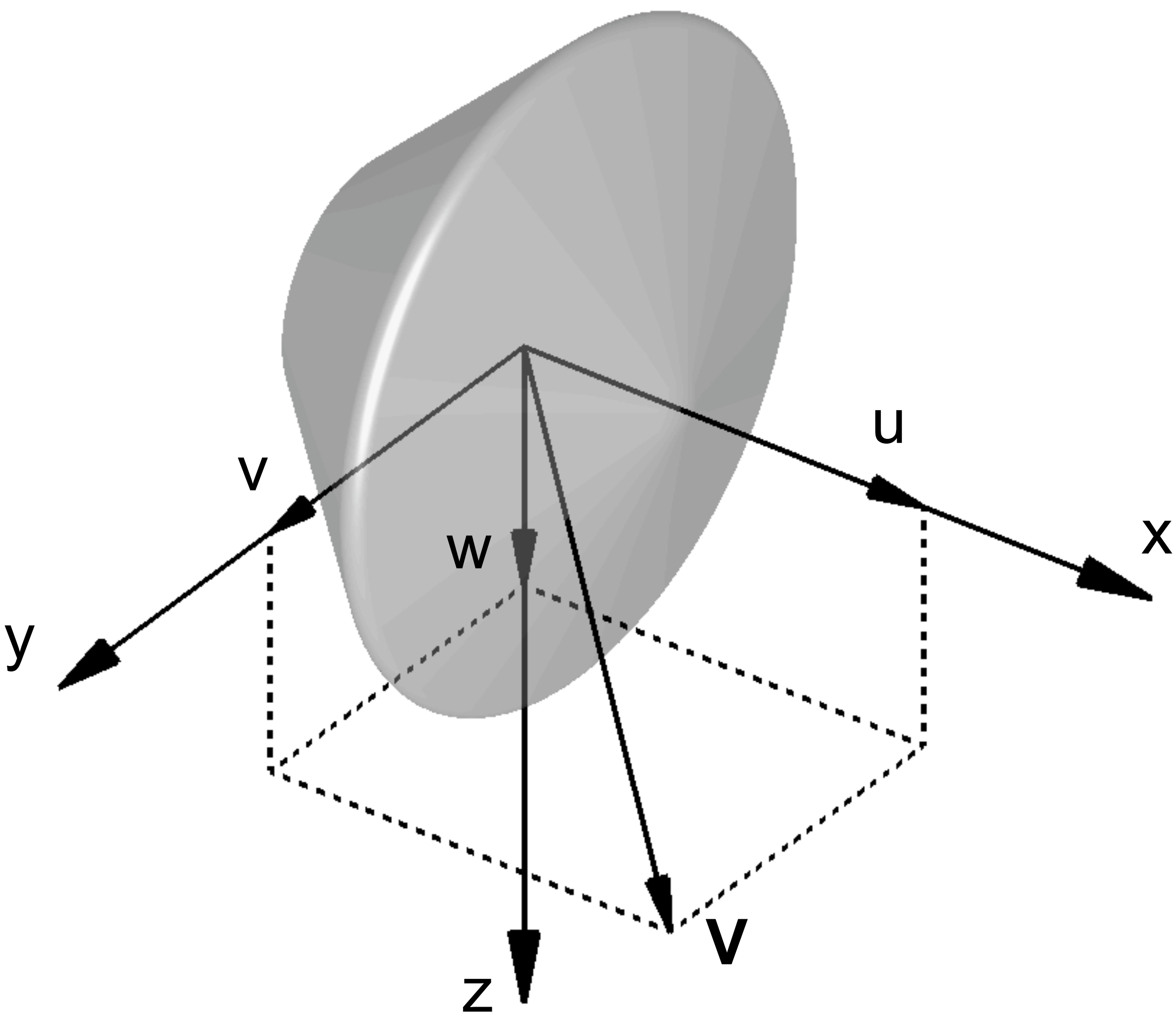
ψ, θ, ϕ - vehicle's attitude; *Euler Angles*

X_P, Y_P, Z_P - vehicle's center of mass location vector

We will need one differential equation for each of these state variables

State Variables - Velocity

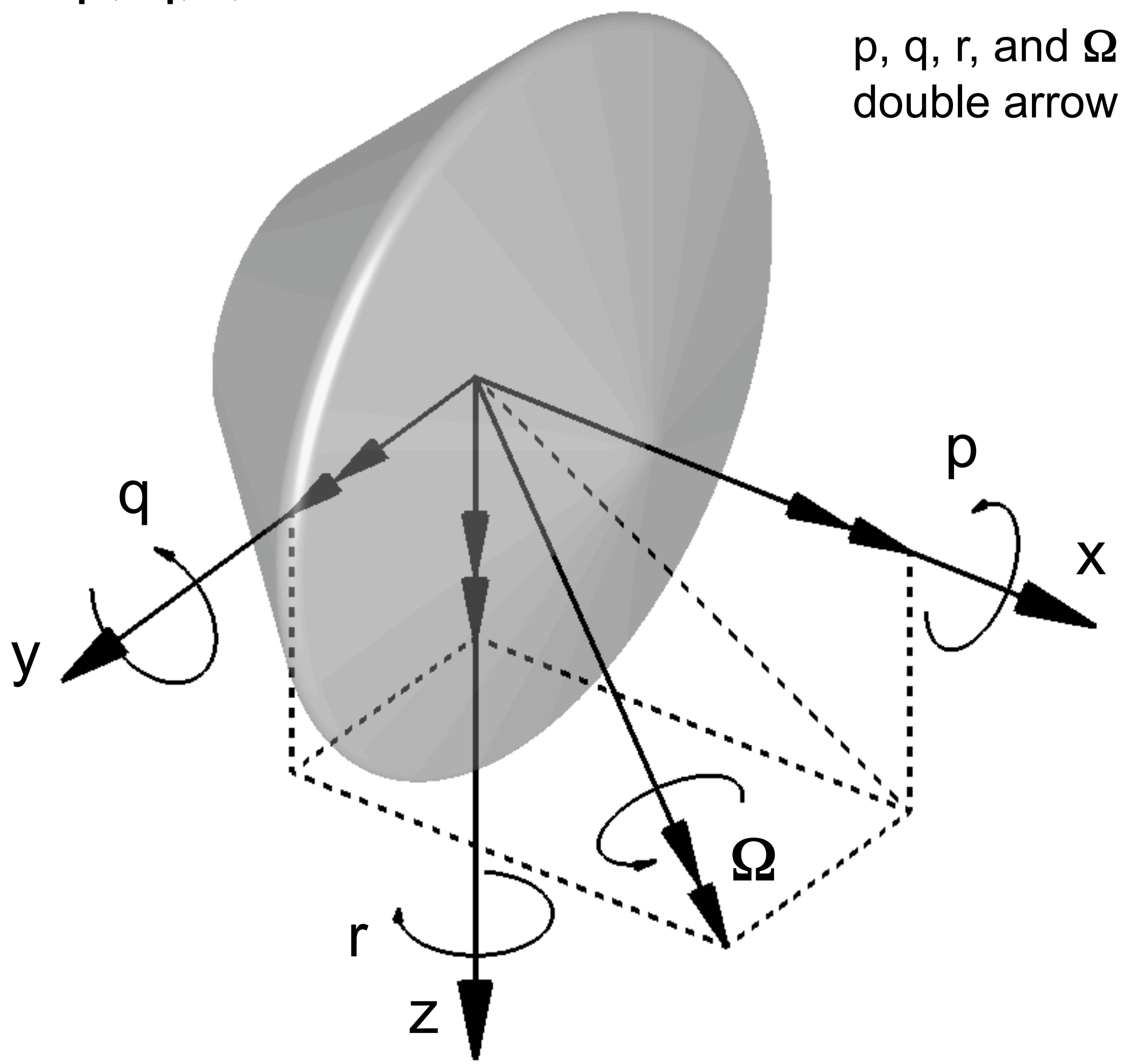
Definition of u, v, w, and **V**



State Variables - Rotation

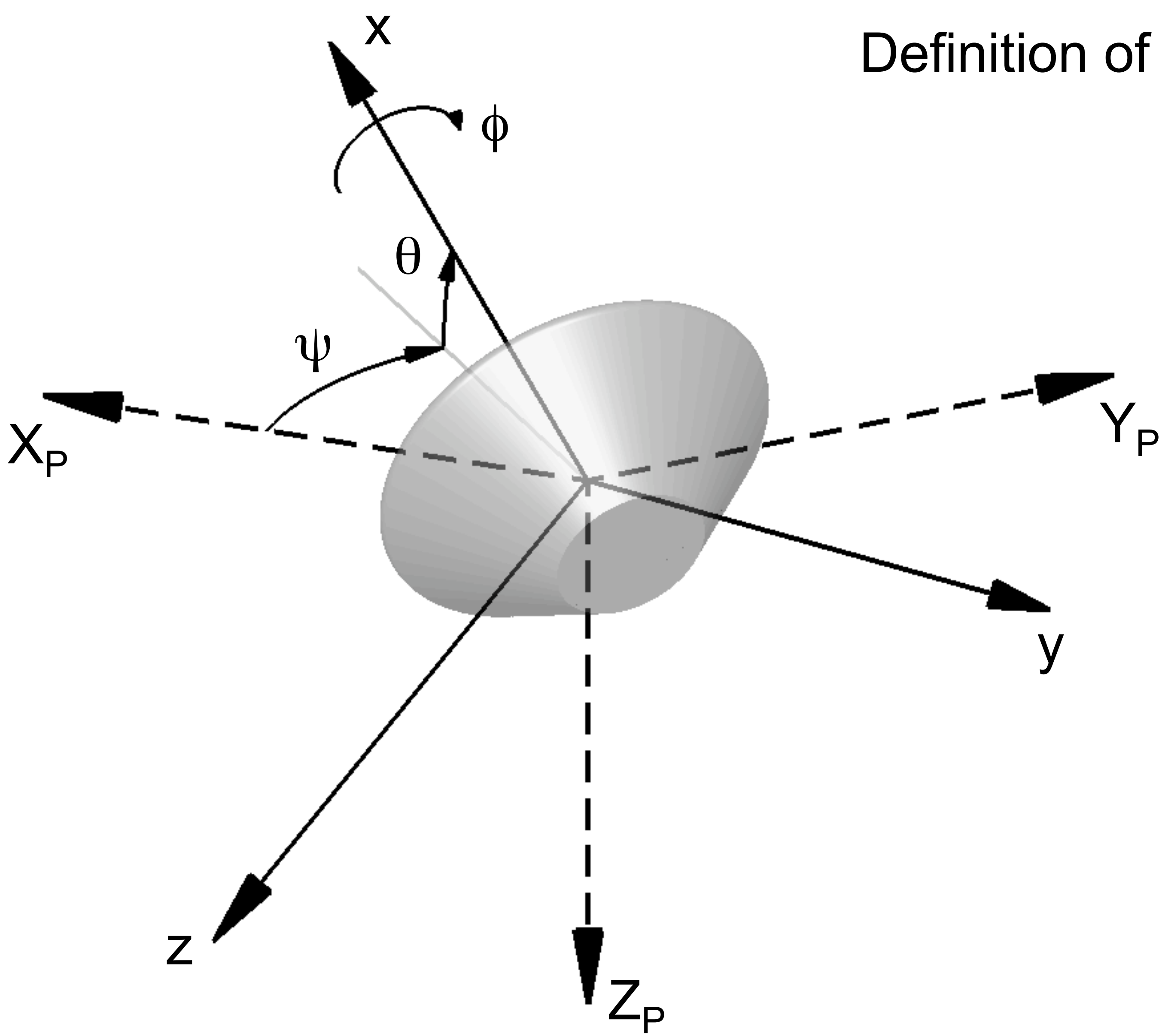
Definition of p, q, r, and **Ω**

p, q, r, and **Ω** are shown by double arrow and arc arrow

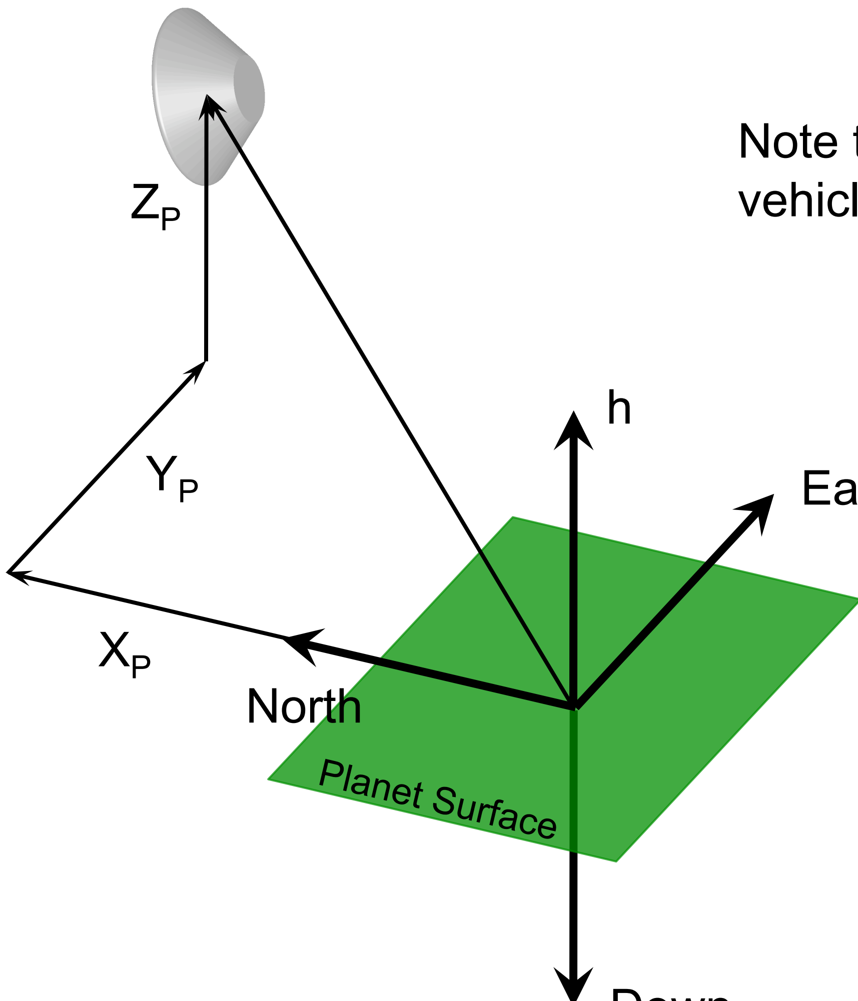


State Variables - Attitude

Definition of ψ, θ, and ϕ



State Variables - Position



Note that $Z_P < 0$ for the vehicle position shown

Equations of Motion

The equations of motion (EOM) can be written conceptually as:

$$[m]\{\dot{V}\} = \{F_{gravity} + F_{propulsion} + F_{aero}\}$$

$$[I]\{\dot{\Omega}\} = \{M_{gravity} + M_{propulsion} + M_{aero}\}$$

These equations are coupled

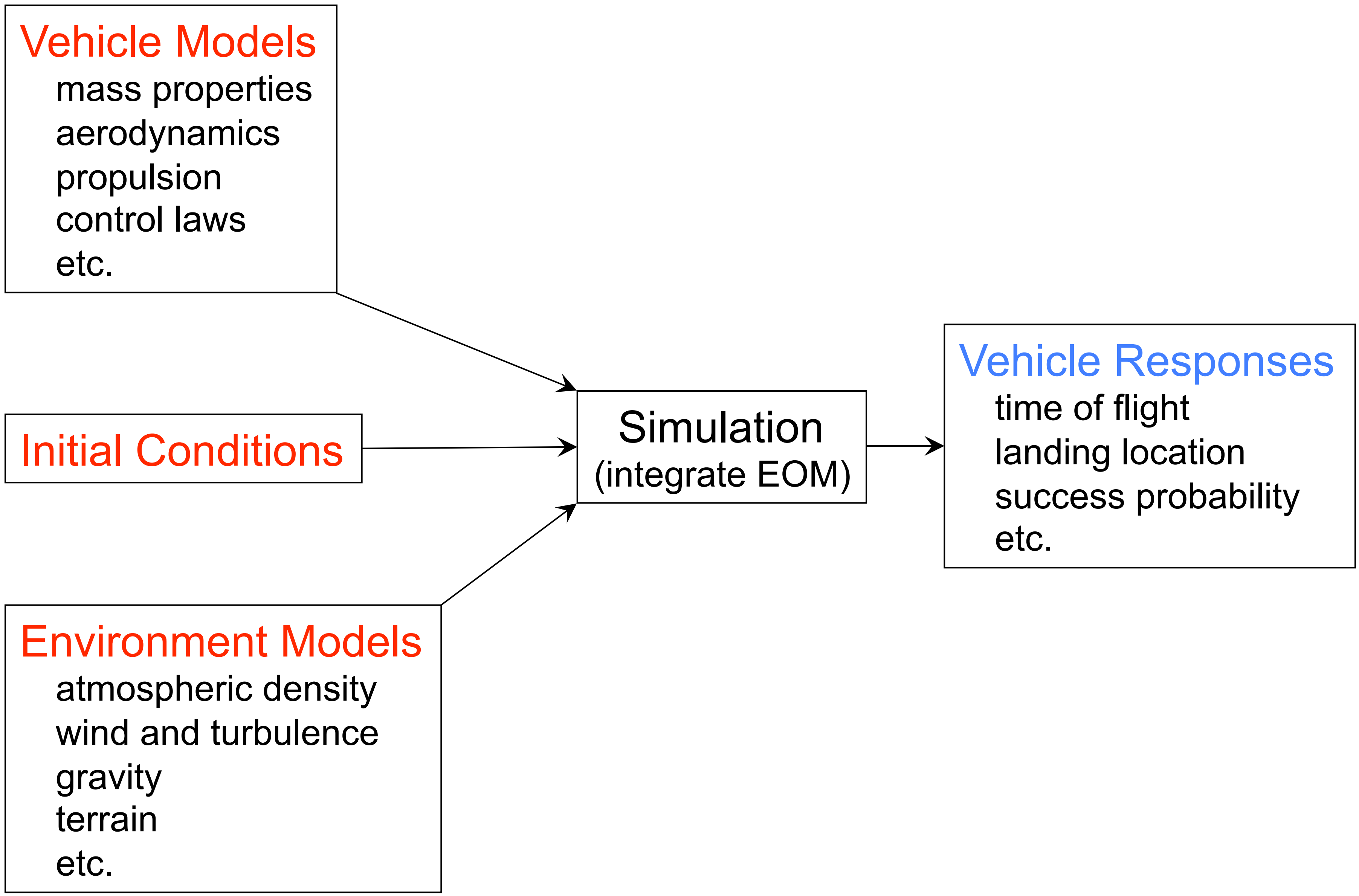
$$\{\dot{\Theta}\} = \{f_Q(\Theta, \Omega)\}$$

$$\{\dot{X}\} = \{f_X(V, \Theta)\}$$

V	-	velocity
Ω	-	rotation
Θ	-	attitude
X	-	position

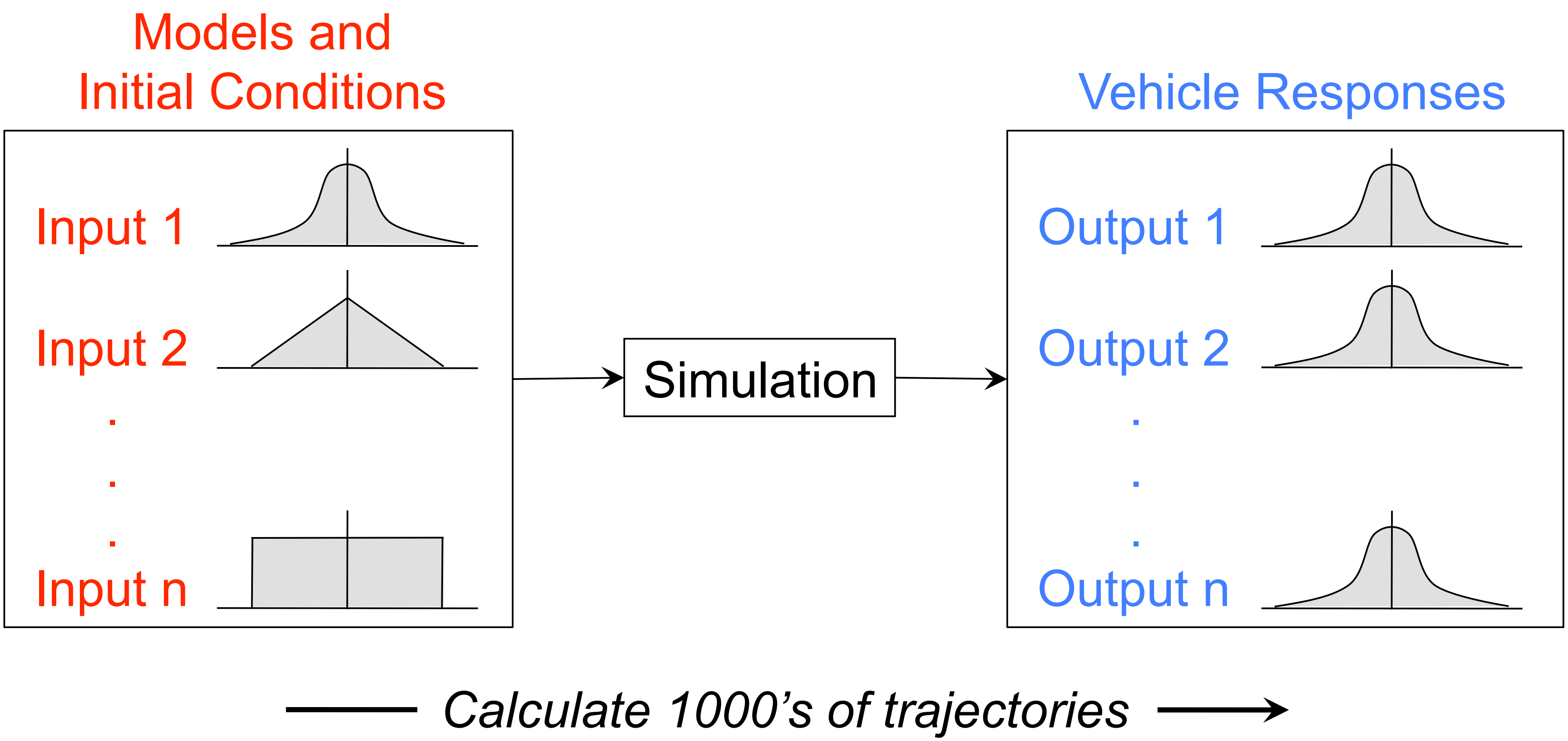
Standard numerical methods are used to integrate the EOM. Significant difficulties arise in obtaining accurate values for the aerodynamic forces and moments, F_{aero} and M_{aero}.

Modeling and Simulation

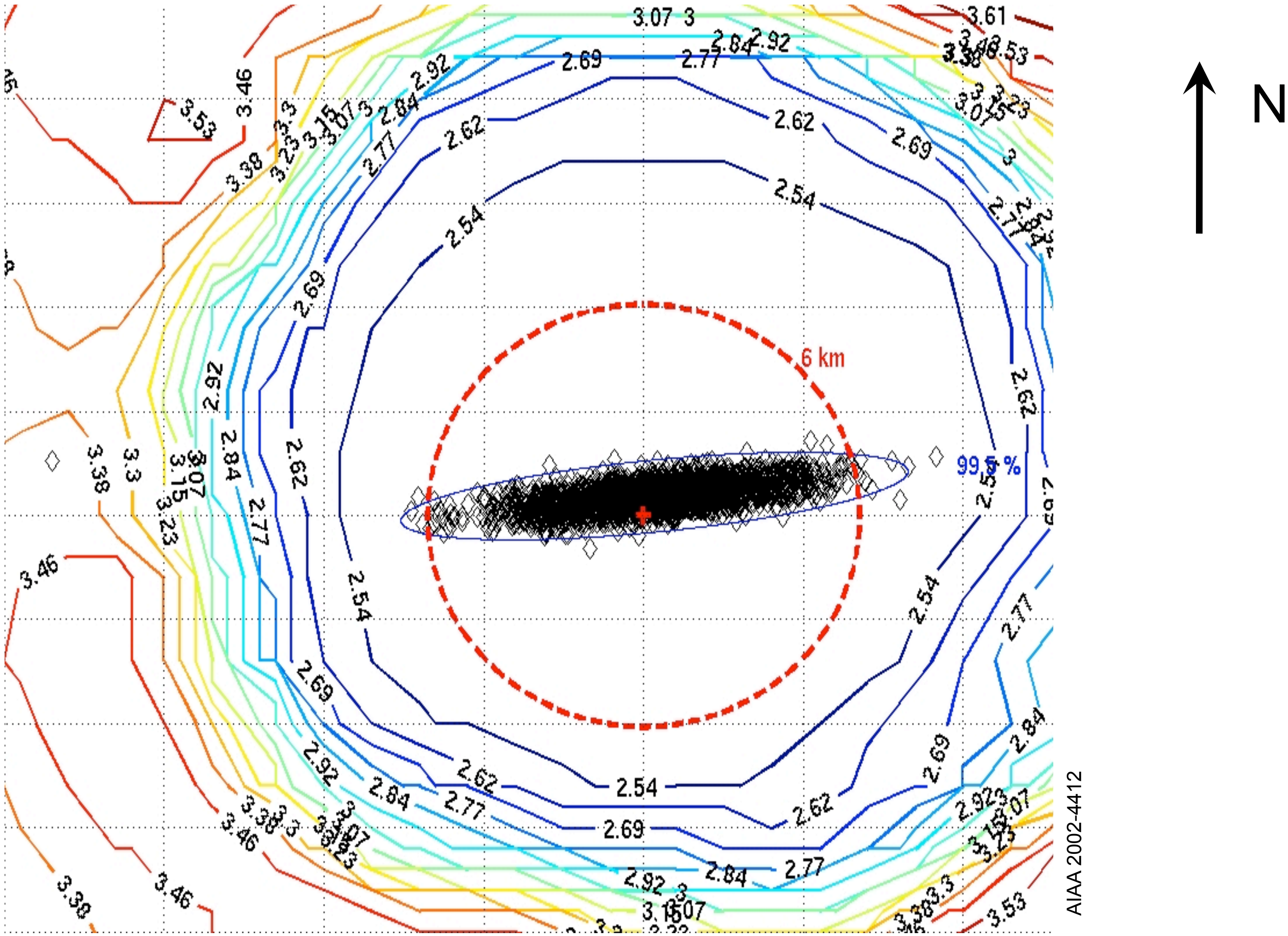


Uncertainty and Monte Carlo Simulation

Values for input quantities related to the vehicle models, initial conditions, and environment models are often only known in a statistical sense. The effect of the uncertainties in these quantities are addressed by executing the simulation 1000's of times using the Monte Carlo method.



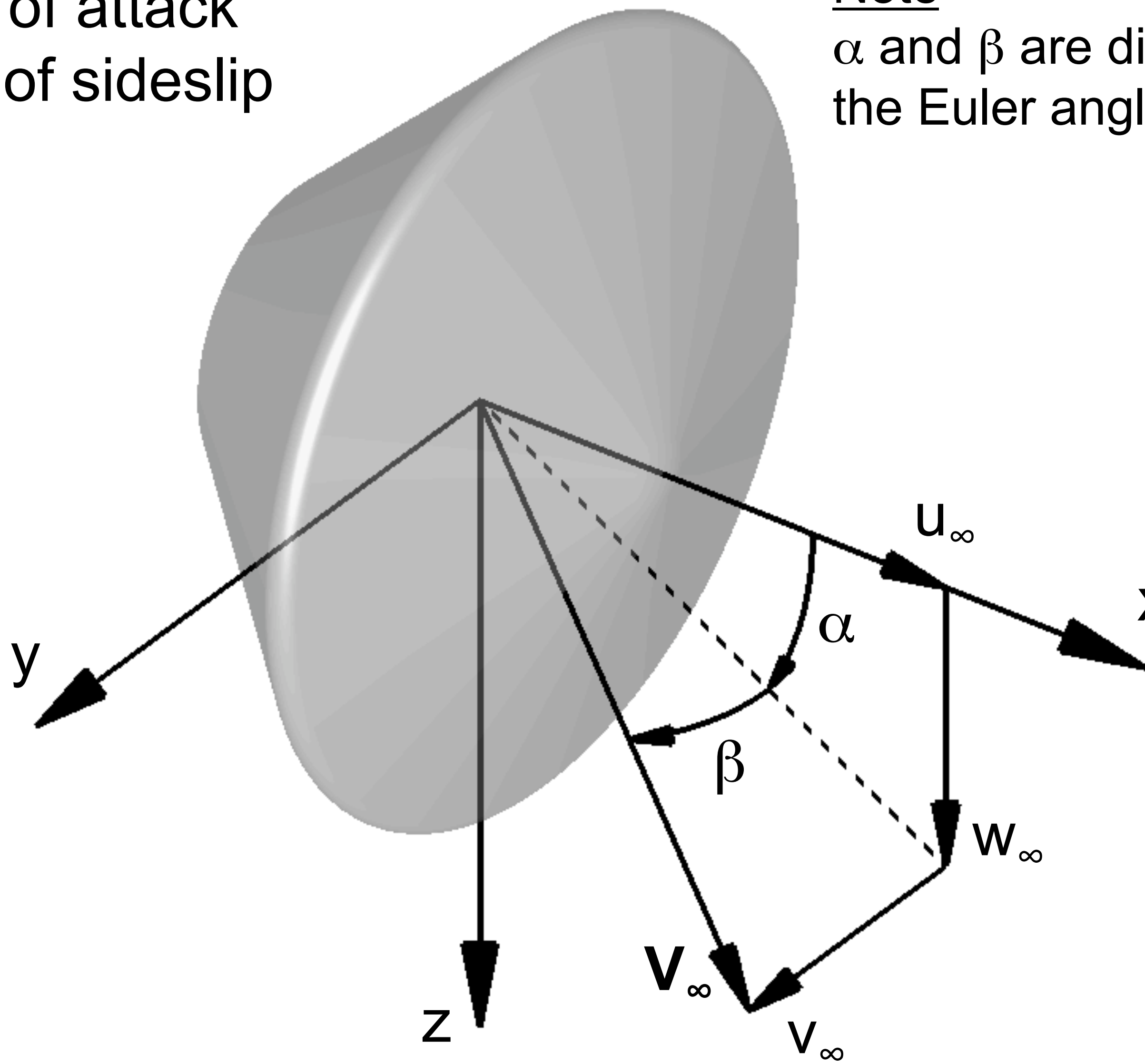
Monte Carlo Simulation Example – Landing Footprint



Wind Relative Angles

α – angle of attack
β – angle of sideslip

<u>Note</u>
α and β are distinct from the Euler angles θ, ϕ, and ψ



Sources of Aerodynamic Data

The needed aerodynamic data can be obtained in several ways:

Static Wind Tunnel Test

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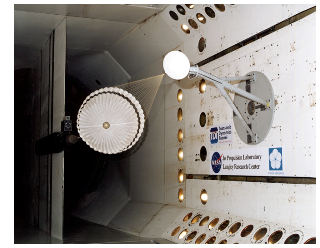

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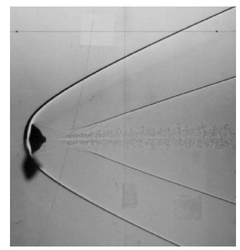
Dynamic Testing



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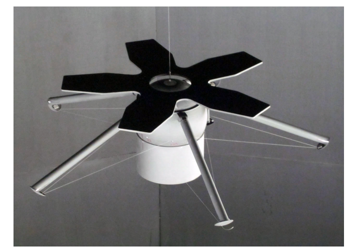
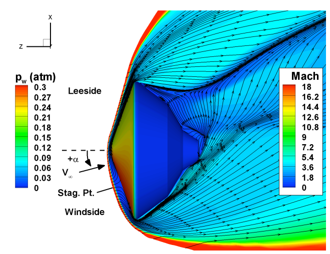


SAGE Venus Lander

Computational Fluid Dynamics



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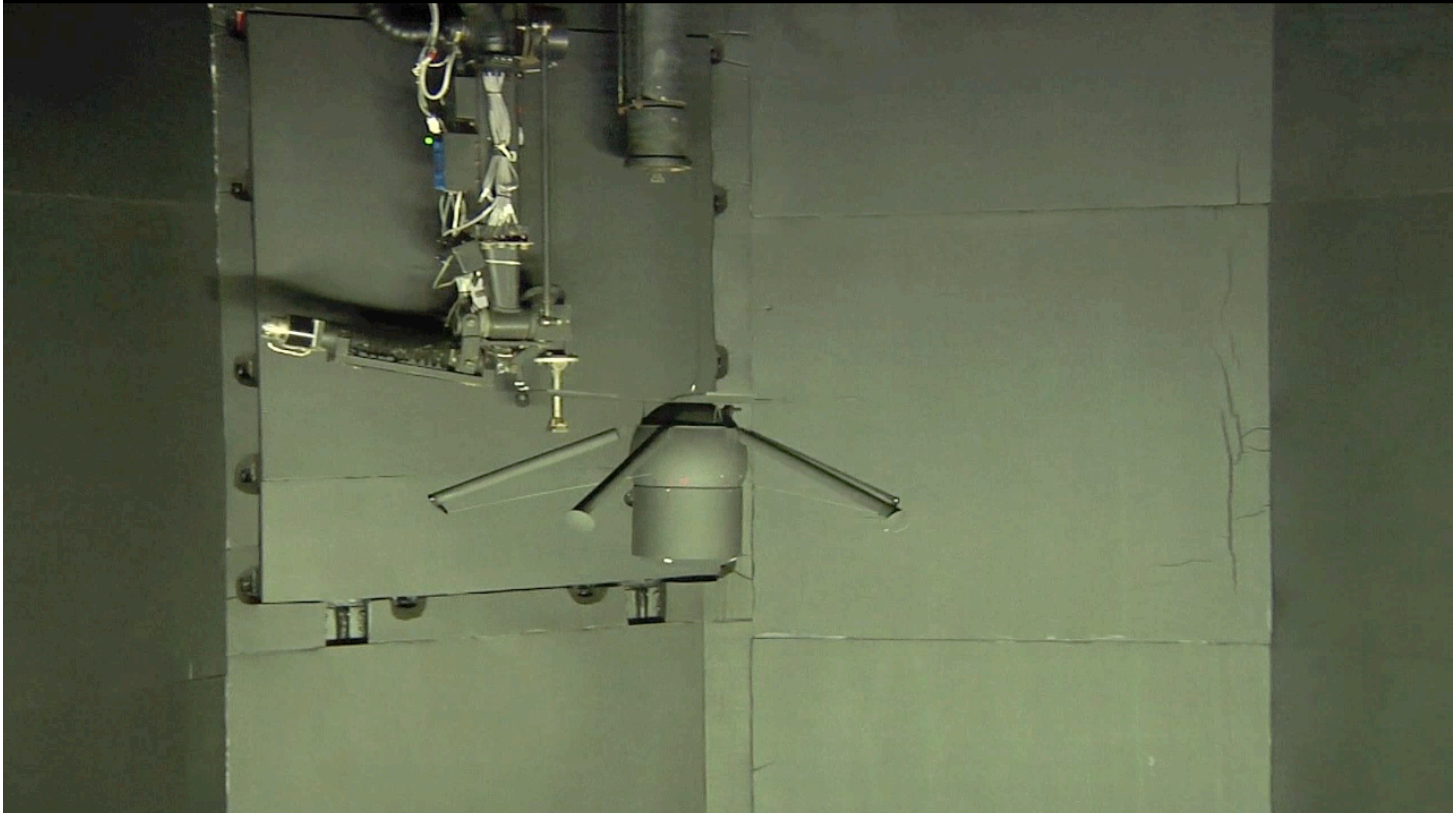
Regardless of the data source, aerodynamics model and data are often approximate and constitute a significant source of the uncertainty in flight mechanics simulations.



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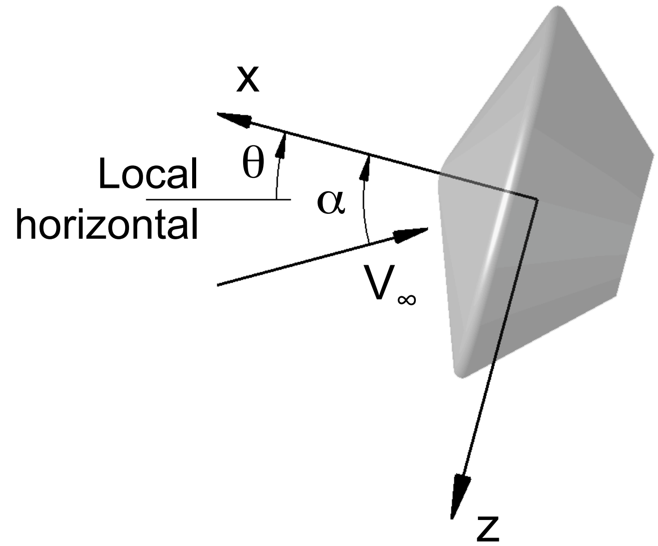
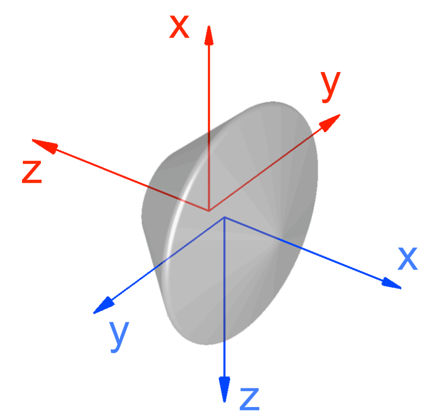
Terminology

- Be rigorous in the use of terminology
    - Example: angle of attack is generally not the same as the pitch angle; $\alpha \neq \theta$



- Be clear on the coordinate system being used
    - The standard body coordinate systems used in flight mechanics is often different than that used by the mechanical systems design team



Flight Mechanics: Blue
Mechanical Systems: Red

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Accuracy of Results

- Numerous assumptions are made in flight mechanics simulations. These assumptions affect the accuracy of the calculated responses.
  - Example: aerodynamic damping derivatives

- The accuracy of calculated responses varies between calculated responses
  - Example: dq/dt (rotational acceleration in pitch) is typically less accurate than q (rotational velocity in pitch)

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<u>Statistics</u>

- Most of the input quantities and calculated responses are best characterized in terms of statistics

- Do not assume that the statistical distribution of calculated responses is normal (Gaussian) – often they are not!
  - Because of this, avoid specifying uncertainty in terms of the standard deviation, σ
  - Useful ways of describing the statistics of a response include

    Histograms and Cumulative Probability Graphs

    Mean, Median, and Percentiles

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Requirements

- Requirements on calculated responses are best specified in statistical, not absolute terms
  - Example: X shall not exceed a value of Y at the 99.5 percentile level

- Be very specific in defining requirements related to calculated responses

  Weak: The rotation rate shall be less than X rad/s

  Better: The magnitude of the rotation rate vector, $|\Omega|$, shall be less than X rad/s 20 percent of the time from event A to event B.

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Environments I

- Environments are critical to accurate simulations

  gravity field

  atmospheric density

  atmospheric speed of sound

  wind

  turbulence

- Some of these environment variables have first-order effects on the flight (e.g., atmospheric density)

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Environments II

- Without some of these environment variables it is impossible to calculate certain responses
  - Example: wind and turbulence models are needed to calculate the flight dynamics of a vehicle in terminal descent

- The flight mechanics team will depend on the science team for definition of some or all of these environments